DATA BUOY OBSERVATIONS: THE *STATUS QUO* AND ANTICIPATED DEVELOPMENTS OVER THE NEXT DECADE

David Meldrum[(1)], Etienne Charpentier[(2)], Mike Fedak[(3)], Boram Lee[(4)], Rick Lumpkin[(5)], Peter Niiler[(6)], Hester Viola[(7)]

[(1)] *Leader, Technology Development, Scottish Association for Marine Science, Dunbeg PA37 1QA Oba, Scotland Email: dtm@sams.ac.uk*

[(2)] *Scientific Officer, World Meteorological Organization, CP 2300, CH-1211 Geneva 2, Switzerland Email: echarpentier@wmo.int*

[(3)] *Mike Fedak, Emeritus Professor, Sea Mammal Research Unit, St Andrews, Fife KY16 8LB, United Kingdom Email: maf3@st-and.ac.uk*

[(4)] *Boram Lee, Scientific Officer, Intergovernmental Oceanographic Commission, 1 rue Miollis, 75732 Paris Cedex 15, France, Email: b.lee@unesco.org*

[(5)] *Rick Lumpkin, Research Scientist, NOAA-AOML (National Oceanic and Atmospheric Administration/Atlantic Oceanographic and Meteorological Laboratory), 4301 Rickenbacker Causeway, Miami, FL 33149, USA Email: Rick.Lumpkin@noaa.gov*

[(6)] *Peter Niiler, Emeritus Professor, Scripps Institution of Oceanography, La Jolla, CA 92093-0213, USA Email: pniiler@ucsd.edu*

[(7)] *Hester Viola, Technical Co-ordinator, JCOMMOPS (Joint World Meteorological Organisation (WMO)/Intergovernmental Oceanographic Commission (IOC) Technical Commission for Oceanography and Marine Meteorology/in situ Observing Platform Support Centre - CLS (Collecte Localisation Satellites), 8-10 rue Hermès, 31526 Ramonville Saint-Agne, France, Email: viola@jcommops.org*

ABSTRACT

This paper reviews the *status quo* of data buoy observations, from both moored and drifting platforms, throughout the global oceans and anticipates the developments and problems that will eventuate over the next decade or so.

1. THE *STATUS QUO* - PROGRESS SINCE OCEANOBS'99

Although by the time of OceanObs'99 data buoys, both drifting and moored, were a relatively mature technology, there still existed a significant divide between those deploying buoys for research purposes (mainly oceanographers) and those that operated buoys as part of a composite operational observing system (entirely meteorologists). The former still showed some reluctance to allow their buoy data to be published openly in near real time (i.e. via the Global Telecommunications System (GTS)), and the latter were becoming increasing frustrated by their lack of access to these data, comprising more than 50% of the global buoy data being collected via the Argos satellite system, the then system of choice of data buoy operators.

The Data Buoy Co-operation Panel (DBCP) had attempted to address this problem since its inception in 1985, and once other fundamental technical issues regarding the quality, quantity and timeliness of data from meteorological buoys had been resolved, this problem was high on the DBCP agenda by 1999. A number of factors acted in favour of the resolution of this problem:

A) The ground-breaking development at Scripps (within the context of the World Ocean Circulation Experiment Surface Velocity Programme (WOCE-SVP)) of a relatively inexpensive compact drogued drifter (the SVP-B (for barometer)) that could be equipped with a barometer and could happily serve the needs of both the oceanographic and meteorological community. This platform has, since OceanObs'99, become the accepted workhorse of the drifting buoy community and, through open sourcing of the design and construction details [1], is now offered by five independent manufacturers: three in the US, one in Canada and one in Ukraine;

B) The creation of an independent processing stream at the satellite company CLS (Collecte Localisation Satellites) Argos, largely funded by the DBCP, to differentiate between buoy data destined for the buoy operator and data destined for the GTS. This had become a major stumbling block for researchers, who could be convinced of the value of making data available to the forecasting community, but who then baulked at the requirement that their buoy transmissions be formatted according to a rigid format (dating from drifter experiments in the late 1970s) and that they would also lose access to their raw unprocessed data;

C) The instigation, through the work of both CLS and the DBCP Technical Coordinator (based at CLS Toulouse) of an effective and stable quality control (QC) procedure, involving both real-time and delayed-mode components [2], that effectively ended the debate regarding the dubious quality of data buoy observations circulating on the GTS;

D) The stipulation, largely within the US (the major buoy deployer), but also elsewhere, that public funds would only be disbursed in support of data buoy programmes if the data were made freely available in real time to the global forecasting community via the GTS.

In direct consequence, the last decade has seen a steady improvement in the quantity and quality, but not necessarily the timeliness, of drifter data being made available to the wider community via the GTS (see Figs. 1, 2, 3 and 4).

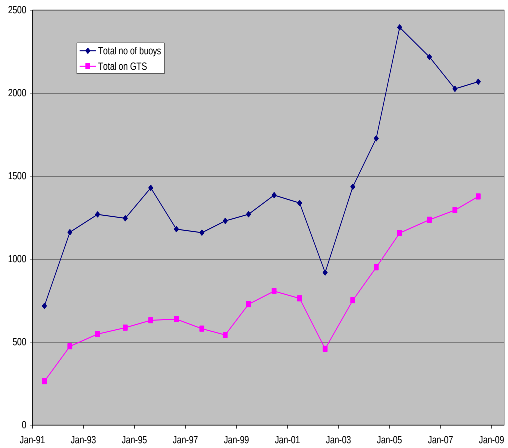

Figure 1. The growth in the number of data buoys reporting via Argos since OceanObs'99.

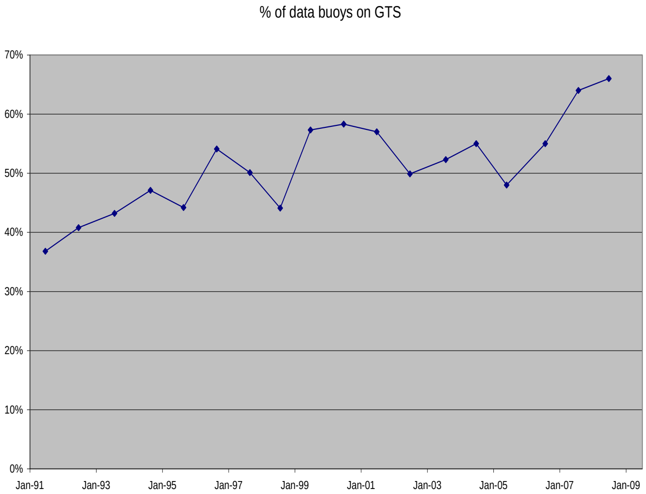

Figure 2. The growth in the percentage of data buoys reporting to the GTS via Argos since OceanObs'99.

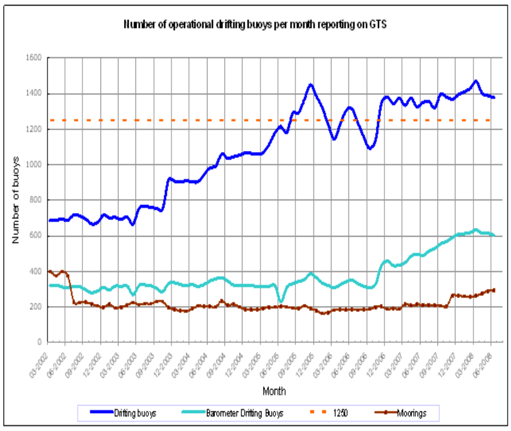

Figure 3. The various classes of GTS-reporting data buoys since OceanObs'99. The dashed line represents the 1250 global target of one drifting buoy per 500x500 km square.

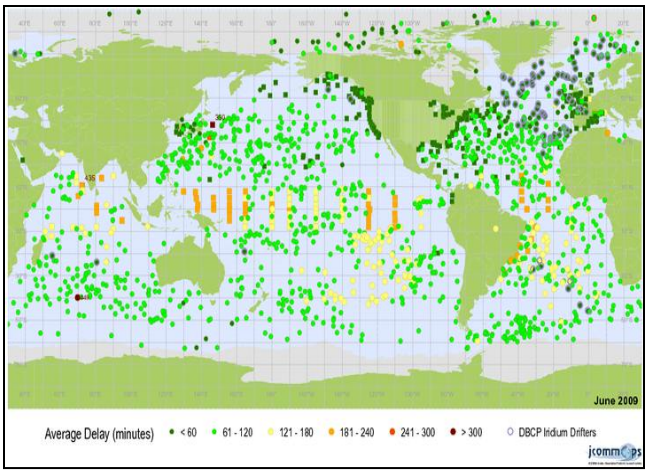

Figure 4. Delays between time of observation and the data being published on the GTS for the global data buoy array. The situation has improved little over the last decade (see Sect. 1.4), and unresolved blind-orbit issues with the NOAA polar orbiters continue to delay drifter data from the S Atlantic and S Pacific. Significant delays are also evident for the tropical moored buoy array, reporting via geostationary satellite.

1.1 Development of the global network of moored and drifting buoys

Since OceanObs'99, a number of initiatives have seen the expansion of the network of both moored and drifting buoys. National agencies throughout the world have been proactive in installing coastal moored buoy networks: increasingly (but not comprehensively) these data are shared via the GTS. Whilst the justification of installing these networks has been parochial, in terms of improving local weather and ocean forecasting, it is to be applauded that nonetheless much of these data are available to the wider community.

The international effort for moored buoys has focused on extending the tropical moored buoy array from its well-established Pacific arena to both Atlantic and Indian Ocean tropical regions. This activity has received additional impetus since the 2004 Boxing Day tsunami as increasingly the consensus is towards the development of multi-use platforms with real-time communications that can serve the entire range of requirements from disaster warning to climate observation. This is an area that will see a steady progress towards rational solution in the coming decade now that the chaotic multi-agency response to the 2004 tsunami has started to focus on realistic and non-political solutions [3].

As regards the drifting buoy fleet, a major milestone was the completion of the global array of 1250 GTS-reporting drifters, largely funded through the NOAA (National Oceanic and Atmospheric Administration) Office of Climate Observation (OCO) and implemented by the NOAA-AOML (Atlantic Oceanographic and Meteorological Laboratory) Global Drifter Program (GDP), in 2005. The current distribution of all buoys reporting via the GTS is shown in Fig. 5 [4]: the poor coverage at high latitudes is an ongoing area of concern. It should be noted that the majority of the drifter fleet does not report sea level atmospheric pressure (SLP), the interests of OCO being focused on the determination of upper ocean heat content via the measurement of sea surface temperature (SST). Nonetheless, the DBCP and the GDP encourage interested national weather services (NWS) to upgrade the SST drifters by the addition of a barometer through the DBCP Barometer Upgrade Scheme [5]. This scheme allows NWSs to receive SLP data that would otherwise be unavailable for a cost of about $1200 per platform. The scheme has been very successful, with a significant proportion of the GTS reporting fleet benefiting from the upgrade.

1.2 Improvements in buoy and sensor technology

The last decade has in general seen a steady improvement in hull, sensor and communications technology and reliability. Particular areas of progress have been in barometer stability and barometer port reliability, drogue attachment and drogue-loss reporting, energy consumption, hull mass-production and drifter packaging for deployment by non-skilled operators. However, as in many other fields of human endeavour, problems that have been fixed do not necessarily stay fixed, and issues have re-emerged around the ongoing supply of Argos transmitter modules, intermittent spiking in pressure records, and the deleterious downstream consequences of apparently subtle changes in production materials and methods.

1.3 Improvements in buoy lifetimes

Little data are available to allow an honest analysis of these important figures of merit for moored data buoys, so this paragraph addresses only drifting buoys, for which an increasing body of evidence is available.

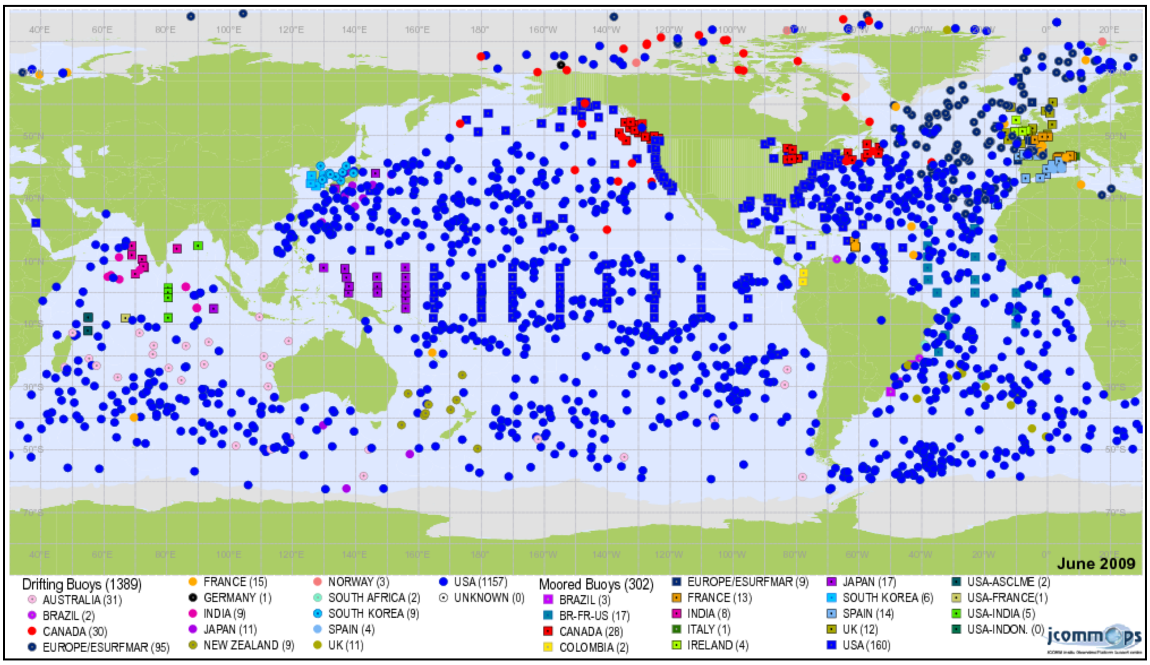

Figure 5. The global distribution of data buoys reporting via the GTS in June 2009, according to country/agency.

For drifting buoys at least, advances in manufacturing techniques and falling component costs (including vacuum forming of buoy hulls and generally cheaper electronics) have been offset by a number of increases, notably in the cost of the pressure sensor used in the SVP-B workhorse. Nonetheless, unit costs of SST-only drifters have fallen by about 30% over the decade in US$ terms, allowing the speedy completion of the 1250 buoy global SST array. This has perversely tended to worsen the potential for the deployment of barometer-equipped drifters required for NWP. In recognition that the two main communities deploying drifters (oceanography/climate as against weather) were driven by somewhat different agendas, the DBCP has for sometime promoted a very successful Barometer Upgrade scheme, whereby national meteorological services could equip SST drifters with a barometer for an incremental cost of $1000. Owing to the increase in barometer costs, this has now risen to $1200, and a mounting tension exists between deploying greater numbers of relatively cheaper SST-only drifters, and funding the relatively expensive barometer upgrade. The tension is heightened by the realisation, in the last decade, that the traditional view that intra-tropical drifters need not be equipped with barometers (owing to the normally weak pressure signal that exists in these regions) is no longer tenable, given that increasingly frequent and catastrophic cyclonic events display a very marked pressure signature.

As regards buoy lifetimes, the picture for drifters is somewhat confused. In part this is because lifetime can be assessed according to a number of metrics (transmit failure, sensor failure, grounding, drogue loss, etc), in part because the statistics can be adversely skewed by 'infant mortalities' and other quantification difficulties. A fortunate consequence of there being five manufacturers producing more or less the same drifter design (the SVP-B), the increasing availability of metadata describing the attributes of each individual drifter, and the painstaking work of the GDP team at NOAA-AOML, is that a better understanding is emerging of true lifetimes and failure modes. Another important output from these studies is to better inform the potential buoy purchaser of the relative merits of individual manufacturers, and so to favour those that are capable of delivering more durable products, whereas previously there was no commercial incentive for a buoy manufacturer to maximise buoy life. Indeed, the opposite.

Ultimately, drifting buoy lifetimes are showing little if any general movement towards the target half-life figure of 450 days (see Fig. 6, courtesy of Mayra Pazos, NOAA-AOML).

1.4 Improvements in value for money

With regard to the cost to the user of each observation, there are clearly many ways of evaluating this key variable, depending critically on the actual value of the observation, the cost and lifetime of the drifter, and the cost of whichever communications system is used. The latter is a case in point, as most US Argos users enjoy a significantly better rate than non-US users under a volume purchasing deal.

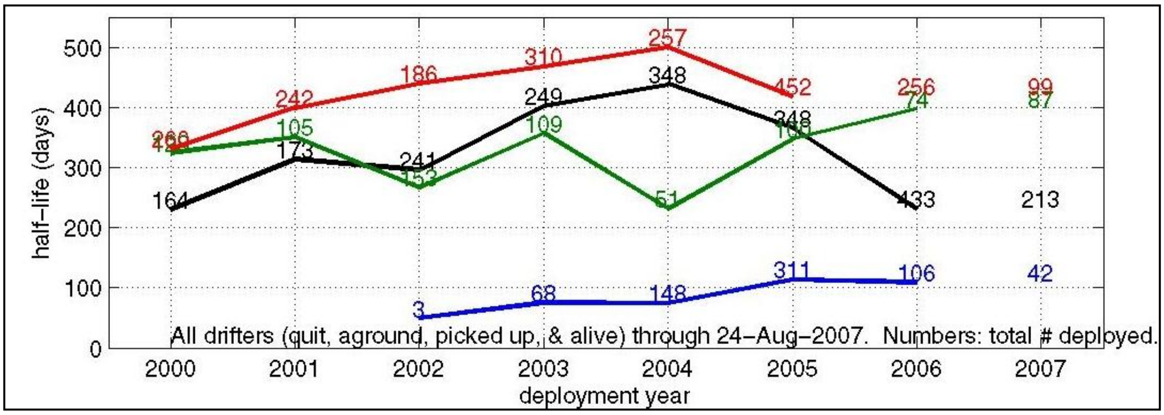

Figure 6. *A comparison of buoy lifetimes from four different manufacturers (courtesy Mayra Pazos, AOML). The trend is only weakly, if at all, positive.*

As an example for a non-US Argos buoy operator, the cost breakdown for a buoy lasting 450 days is shown in Fig. 7, alongside a similar chart (Fig. 8) for an Iridium drifter. Iridium drifter lifetimes have yet to reach the figures being achieved by Argos, though there is no technical reason why they should not, and lifetime operating costs will soon fall to little more than half of the figure faced by non-US Argos users. Coupled with the better timeliness of Iridium observations, largely resulting from their much denser constellation, (see Sect. 1.5) the case for moving to Iridium might be seen to be compelling. However, Iridium (unlike Argos) does not primarily serve an environmental mission, and a number of issues need to be solved regarding GTS formatting, QC and distribution of the data.

As regards the unit cost of an observation, assuming each drifter reports hourly, the costs for non-US Argos are currently approx $0.7 per observation, compared with roughly $0.4 for Iridium. The total annual running cost (hardware and communications, but excluding deployment) of the entire 1250-drifter network is about $2.5M, small in comparison to the costs of most other observing systems. As regards the benefits of the drifter array, impact studies have shown the importance of drifter pressure observations in forecasting dynamical weather events, and the importance of drifter SST for satellite validation and ocean climate studies.

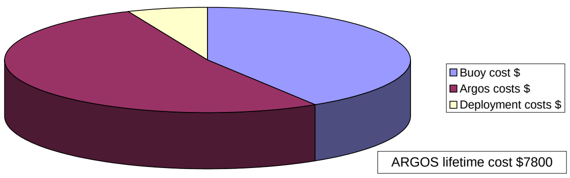

Figure 7. The cost breakdown for a non-US Argos-equipped drifter with a notional lifetime of 450 days. The communications costs account for half of the total cost.

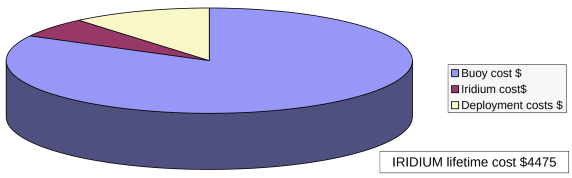

Figure 8. The cost breakdown for an Iridium-equipped drifter with a notional lifetime of 450 days. Cheaper communications lead to a greatly reduced lifetime cost.

1.5 Progress with communications systems

For most of the last decade, almost the entire drifting buoy fleet has reported via the Argos satellite system, carried by the NOAA polar orbiters and more recently by the first of the European METOP satellites. Argos have continued their upgrade programme for both the space and ground segments, with satellite receivers now offering considerably greater capacity than before, and the ground segment being expanded by the addition of further direct readout stations as a means of improving data timeliness. Traditionally Argos platform transmissions were unacknowledged ('blind' transmission) as the system was one-way only: now a two-way system is flying on METOP-A (Meteorological Operational Satellite) and is currently under evaluation. The expansion of the direct readout network to more than 50 stations has improved data timeliness over the major part of the world's oceans, with an increasing proportion of traffic now reaching the GTS via this route (Fig. 9). Timeliness has improved for this reason alone, as actual delays for both direct-readout and stored datasets have shown little, if any, improvement over the last decade (Figs. 10 and 11). Notable exceptions to the general improvement are in the South Atlantic and South Pacific where no direct readout coverage exists, and data are stored on board the satellite for eventual download via the three main NOAA global ground stations situated in Virginia, Alaska (USA) and Svalbard (Fig. 4). Ironically, the areas worst affected by lack of direct coverage are those for which stored data delays are worst owing to many of the relevant orbits not being seen by the US global ground stations until many hours have passed (the so-called blind orbit problem). Even worse, the NOAA Svalbard station, which is capable of downloading these data promptly, is unlikely to be able to deliver datasets for the older satellites that currently comprise the operational constellation

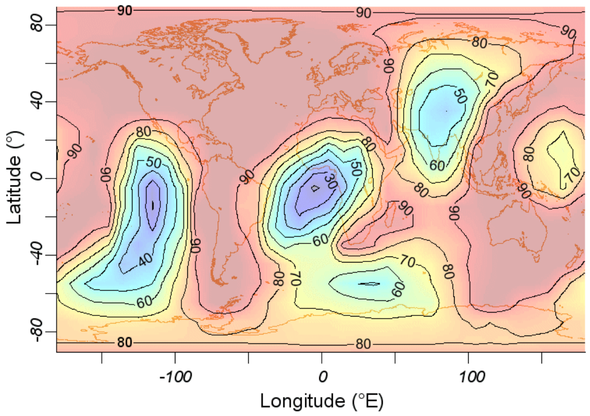

Figure 9. For the Argos system, the percentage of data delivered via the direct readout network. Note the poor oceanic coverage in the South Atlantic and South Pacific, where the most of the data still arrive as stored datasets.

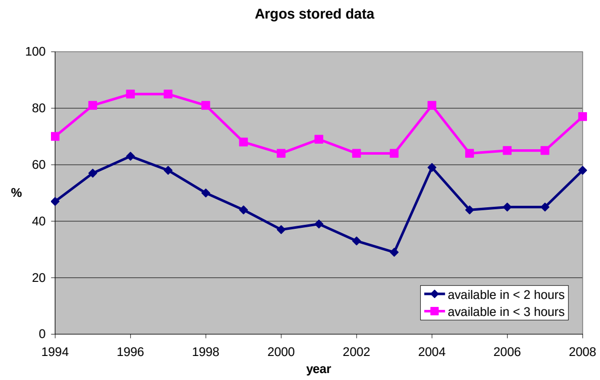

Figure 10. For Argos stored datasets, the global trend in reporting delays since 1994. The recent up-turn probably stems from the improved timeliness of METOP-A datasets arriving via the European Svalbard station.

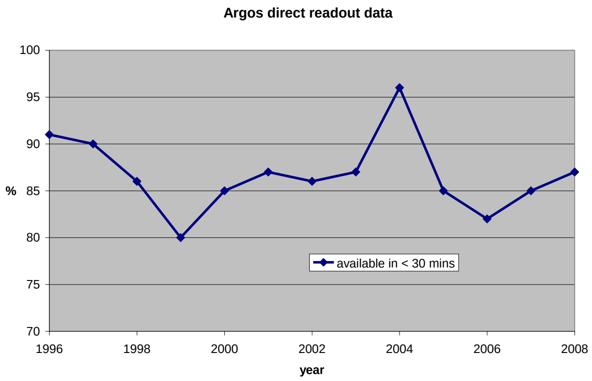

Figure 11. For the much more timely Argos direct readout datasets, the global trend in reporting delays since 1996, The vast majority of data are available within 30 minutes, but not all ocean areas benefit from this service.

Figure 12. The Iridium system (dark blue line) offers even more timely delivery, with the vast majority of the data reaching the GTS within 25 minutes of the time of observation. Other plots are for Argos platforms in the same ocean area.

The Iridium satellite system is a relative newcomer to the field of environmental data collection, having originally been devised for global mobile telephony. Nonetheless, data services have emerged as a key part of its product portfolio, and, like Argos, it does feature coverage of both poles. It offers a number of important advantages compared to Argos, including continuous on-demand availability anywhere on the globe, nearly instantaneous data transfer from mobile to end user, and higher bandwidth coupled to lower energy demands and generally cheaper costs. The system has been trialled in a number of environmental applications, notably the DBCP Iridium Pilot Project, which has seen roughly 100 successful deployments worldwide. Data timeliness has proved to be excellent, with nearly 100% of data reaching the GTS within 25 minutes of the time of observation (Fig. 12).

1.6 QC systems and data management

As noted earlier, the QC implemented for data flowing to the GTS via the Argos system consists of two major components, a real-time gross error checking procedure, supplemented by a delayed mode protocol that relies on contributing agencies (generally national weather services) posting detailed concerns about individual platforms on a central mail server according to a prescribed format. This process has worked well, and in general, the quality of real-time buoy observations (moored and drifting) continues to improve, as measured by the deviation from background fields or by the numbers of observations ingested by NWP models. This is in part the result of improved models, but is mainly due to improved sensor stability, sampling algorithms and QC procedures. Delayed-mode QC is also invoked by major buoy operators such as the Global Drifter Program at NOAA-AOML, NOAA-NDBC (for moored platforms), and archiving agencies such as Canada's Integrated Science Data Management (ISDM, formerly MEDS) organization. Note that real-time QC has not yet been uniformly implemented by parties inserting Iridium data on to the GTS, of whom there are now at least four. Given its origins in unravelling chaotic QC processes, the DBCP is greatly concerned by this and is taking active steps to avoid a repeat of the early days of Argos drifter observations.

An example of the improvement in real-time data is shown in Fig. 13 for the percentage of drifter sea level pressure observations that show an RMS deviation of <1hPa with respect to the ECMWF (European Centre for Medium-Range Weather Forecasts) first guess field. The mean deviation is currently about 0.85 hPa. Similar improvements are being seen with SST (RMS <0.4C) and wind speed (RMS <1.5 ms^{-1}), with drifter SST now proving to be more reliable than either moored buoy or ship SST. The quality of wind spectral data from moored buoys continues to be an area of concern, and the DBCP has joined with other experts from within the Joint Technical Commission for Oceanography and Marine Meteorology (JCOMM) to initiate a pilot project to examine ways of making improvements in this area.

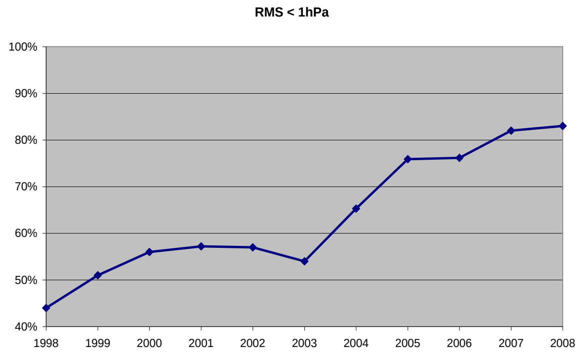

Figure 13. The quality of drifter sea level pressure observations has continued to improve over the last decade, with more than 80% of observations now deviating from NWP first guess fields by <1hPa.

In other areas of data management there has been an increasing demand for instrumental metadata in recent years to serve a number of applications, and climate studies in particular. The DBCP has established its own metadata collection system at JCOMMOPS and is participating in the water temperature metadata Pilot Project (META-T). In addition, the Panel has supported the establishment of a JCOMM Pilot Project on Wave measurement Evaluation and Test from moored buoys (PP-WET). The project will investigate ways if improving the quality and reliability of wave spectral measurement from moored buoys. As regards instrument best practices, the DBCP has appointed a new task team to address these and other quality issues, particularly in regard to the upcoming WIGOS) World Meteorological Organization Integrated Global Observing System) requirements.

1.7 Global co-ordination and evaluation

The DBCP has been at the centre of the global co-ordination of data buoy activities since 1985 and has established a solid reputation for the establishment of effective and realistic protocols for the management and distribution of buoy data, in offering support to data buoy operators worldwide, and in transitioning sensors and systems from the laboratory to the operational arena. This has largely been achieved though the appointment of a technical coordinator, currently based within CLS Argos at Toulouse and funded through member contributions, who is charged with promoting the DBCP's mission, monitoring the performance of the data buoy fleet, and initiating remedial actions as necessary. Regional ownership of data buoy issues has been promoted by the creation of action groups for specific regions and for specific categories of buoy platform. DBCP sessions, open to all, are held annually and transact business in a relatively informal and efficient manner. The intersessional business of the DBCP is delegated to a small executive body and a number of task teams covering areas such as data management, QC, capacity building and technical evaluation.

This latter function has long been a vital component of the DBCP mission, and has in recent years since the funding by the DBCP of a number of pilot projects of limited duration for the evaluation of new technologies such as Iridium, Argos 2-way, and the recovery of useful 2D wave spectral data from both moored and drifting platforms.

1.8 Data analyses and products

A number of DBCP products, such as interactive maps, status plots, guides, meeting documentation and relevant links are available via the DBCP website at www.jcommops.org/dbcp. This site is currently in the process of being upgraded.

1.9 Interaction with the end-user community and with other observing systems

The DBCP has also organized a number of workshops to foster interaction and collaboration with practitioners from other observing systems and with end users to ensure that the data buoy community is well placed to address observational requirements in the decade to come.

Recent events have been held at ECMWF, Ostend and in New York. The outcome of these workshops is translated into DBCP policy through revisions to its implementation plan and working practices, and through the creation of pilot projects to focus on particular issues.

1.10 Ongoing issues

1.10.1 Deployment opportunities.

The issue of inadequate deployment opportunities is now the major difficulty affecting the global dispersion of the drifter array, an issue which is shared with the Argo programme. The Southern Ocean and Gulf of Guinea continue to prove particularly troublesome. The DBCP and Argo Technical Coordinators are working together to identify shared deployment cruises: opportunities for 2009 include the following:

- Maintenance cruises for the TAO (Tropical Atmosphere Ocean) extension in the tropical Indian Ocean (RAMA (Moored Array for African-Asian-Australian Monsoon Analysis and Prediction);
- Cruises of German research vessels;
- Japanese Arctic cruises for the deployment of buoys in the Northern Pacific Ocean. The ship in use for the next two years is the R/V Mirai;
- The DART Tsunami buoy deployment and maintenance cruises will provide an ongoing opportunity in the Pacific and Central Atlantic Oceans. Cruise planning is completed each year by the NOAA National Data Buoy Center (NDBC); and
- The Partnership for Observation of the Global Oceans (POGO) Research Cruise database also contains potentially useful information.

1.10.2 Existing networks - enhancements needed.

Although the statistics for data availability collected by the various operational and archiving centres do not always fully agree, and despite the completion of the global drifter array in September 2005 with the deployment of drifter ‘1250’ offshore from Halifax, Nova Scotia, it is clear that the existing networks do not approach the required observational density in a number of areas, viz the:

- global oceans (waves);
- tropical oceans (P, waves);
- tropical Indian Ocean (wind, waves);
- Arctic (P);
- North Pacific Ocean (SST, P);
- North East Tropical Pacific Ocean (SST, P);
- Arabian Sea (SST, P);
- Gulf of Guinea (SST, P); and
- Southern Ocean south of 40 S (SST, P, waves).

The JCOMM Observations Coordination Group (OCG) has made recommendations to achieve better global coverage. Deployment and re-seeding strategies will be developed which optimize the expenditure of available resources, and which allow accurate and credible prediction of future resource requirements, and their relation to declared objectives. A method has already been developed by NOAA-AOML for this purpose using a simple model to forecast the probability of having buoys in specific regions 90 days in advance.

1.10.3 New observations urgently required.

Surface atmospheric pressure and wind: Equatorial areas, where the atmospheric pressure signal is typically weak, would benefit from a greatly increased density of wind observations but requirements for accurate *in situ* pressure measurements from these regions have also been expressed by NWP at a resolution similar to the global drifter array (i.e. 500km x 500 km). Spatial surface air pressure coverage is marginal for marine services applications. Mean sea level pressure is vital to detect and monitor atmospheric phenomena over the oceans (e.g., tropical cyclones) that significantly constrain shipping. Even very isolated stations may play an important role in synoptic forecasting, especially when they point out differences with NWP model outputs. Plans are therefore underway to install barometers on all drifters by 2012. Whereas the equatorial Pacific is adequately sampled by the moored TAO and TRITON (Triangle Trans-Ocean Buoy Network) arrays, and the PIRATA (Prediction and Research Moored Array in the Atlantic) programme is addressing the sparsity of observations in the tropical Atlantic, the Indian Ocean is currently almost devoid of accurate *in situ* wind measurements, although plans are being drawn up for the establishment of a moored buoy array in the area.

High temporal resolution SST: The Ocean Observations Panel for Climate (OOPC) has also expressed the requirement for collecting and transmitting high temporal resolution (i.e. at least hourly) SST measurements from all drifters in order to resolve the diurnal cycle of SST and the foundation temperature. This, and high-resolution requirements in space and SST, are an area of ongoing negotiation and productive collaboration with the Group for High Resolution SST measurements (GHRSST), whose needs are driven to improve the quality of satellite SST recovery.

Wave observations: In situ measurements are currently too sparse in the open ocean. The vast majority of existing wave measurements is made in the coastal margins of North America and Western Europe, with a huge data void in most of the rest of the global ocean, particularly in the southern ocean and the tropics, while other existing observational systems have often considerable coverage in these areas. The JCOMM Expert Team on Wind Waves and Storm Surges (ETWS) has called for additional wave measurements comprising, at a minimum, significant wave height, peak period and 1-D spectra, hourly in real-time, for assimilation into coupled atmosphere-ocean wave models for real-time forecasting activities, and subsequent verification. These are required for Maritime Safety Services, calibration / validation of satellite wave sensors, the description of the ocean wave climate and its variability on seasonal to decadal time scales, and the role of waves in the coupled ocean-atmosphere system, and their inclusion in weather and climate models. Satellite bias correction validation requirement is for average 1000km spacing with minimum 10% / 25cm accuracy for wave height and 1 second for wave period. Considering the lack of wave data, the DBCP is inviting buoy operators and DBCP members to increase wave measurements, particularly from open ocean areas, in the Southern Ocean, and the tropics. Wave measurement technology issues will also be considered by the DBCP.

Sea level observations: Tsunami and storm surge-prone basins (e.g., Bay of Bengal, Gulf of Mexico and Pacific Islands) require higher density of sea level observations accompanied by observations of atmospheric pressure, and if possible winds and other environmental parameters.

The observational challenge posed by 4-D assimilation schemes: Recent studies using models that allow assimilation of non-synoptic-hour data have demonstrated the positive impact of such data. In particular, the inclusion of hourly extra-tropical buoy data was found to significantly, improve forecast quality, particularly in the southern hemisphere. Non-synoptic-hour data is not routinely reported by all buoys, nor is its insertion on the GTS by Argos currently supported. In both cases, little change would be needed to current practice to allow these additional data to be made available to forecasters.

1.10.4 Vandalism.

This is an important issue affecting moored buoys, especially in the Indian Ocean, where the integrity of the tropical array of both met-ocean and tsunameter buoys is continually compromised by vandalism. Attempts at educating the fishing community as to the purpose and direct benefit of the array in terms of improved warnings and forecasts have so far produced little in the way of tangible results. A more promising line seems to be in the development of vandal-resistant mooring designs that are difficult to board, have few external parts and require special tools to dismantle (see Fig. 14).

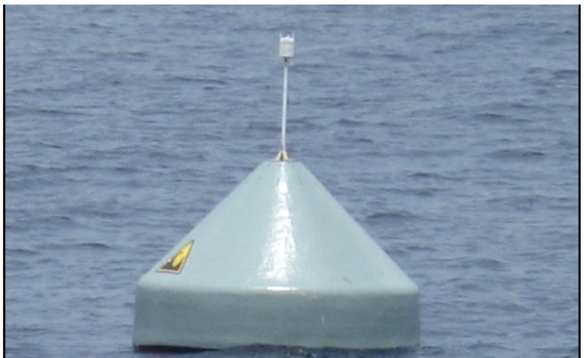

Figure 14. A 'cone-head' moored; buoy being developed by NOAA-PMEL to help combat the vandalism that is prevalent in some regions.

2. FUTURE TRENDS AND CHALLENGES

2.1 Identifying and responding to new user requirements

This task is not as easy as might seem to be the case. End users in operational forecasting centres may have such difficulties in dealing with existing requirements that the prospect of having to deal with new requirements and variables exacerbates their already high stress levels, and they may well have a disincentive with regard to engaging in the process. On the other hand, higher-level 'end users' such as GCOS and similar bodies do not always give fully credible justification for their resolution and accuracy requirements. One way that the OceanObs'09 process can hopefully contribute to this problem is by creating a mechanism that evaluates the disparate needs stated within the community and establishes a consensus view that is capable of being translated into action.

2.1.1 New variables.

The following list is not exhaustive, but identifies a number of the variables for which needs have been expressed by the ocean and climate forecasting community [6]. A particular challenge is in the measurement of biological variables, where existing sensors generally rely on optical measurements, with attendant bio-fouling problems. This is an area that still awaits satisfactory resolution. The list is ranked in decreasing order of readiness for widespread implementation.

- Sea surface salinity
- Wind speed and direction
- 2-D wave spectra
- Precipitation
- pCO_2
- pH
- Nutrients
- Phytoplankton

2.1.2 New ways of measuring existing variables.

Sensor technology is continually developing and more stable low-cost sensors for the measurement of variables such as temperature and wind speed are emerging. A major cost element of many drifting buoys is the requirement to measure absolute sea level pressure with an accuracy of better than 1hPa over the life of the buoy. Over the next decade studies will evaluate the possibility to replace the expensive barometric sensors in a significant portion of the drifter fleet with lower cost sensors that nonetheless are capable of accurately reporting changes in pressure ('pressure tendency').

2.1.3 Enhanced resolution and accuracy.

A number of groups are now requesting that data buoys report observations with increased resolution and accuracy. This is particularly true within the remote sensing community, where data buoys may be the only source of globally distributed *in situ* observations for calibration and validation of satellite sensors. A good example of this is satellite SST retrievals, whose accuracy is now limited by the quality of drifter SST. The DBCP is working closely with the Group for High Resolution SST (GHRSST) to roll out the next generation of HRSST drifters, equipped with improved sensors and GPS, and reporting observations with higher resolution than is available with the traditional GTS character codes. Enhanced resolution and accuracy comes at a price, initially at least, and the additional cost needs to be weighed against the likely benefits.

2.1.4 Distribution in space and time.

As noted in 1.10.1 and Fig. 5 above, the distribution of data buoys is not as uniform as might be desired. There are a number of reasons for this. Firstly, drifting buoys do of course drift, although the speed is limited by the presence of the drogue. In areas where the surface current is divergent, e.g. the Gulf of Guinea, drifter numbers will tend to be lower than wished. The DBCP and the US Navy are now engaging with agencies in West Africa to allow this region to be re-seeded on a regular basis. Analysis of decades of drifter data, notably at NOAA-AOML, has allowed the establishment of seasonal surface current climatologies for most parts of the global ocean (see Fig. 15).

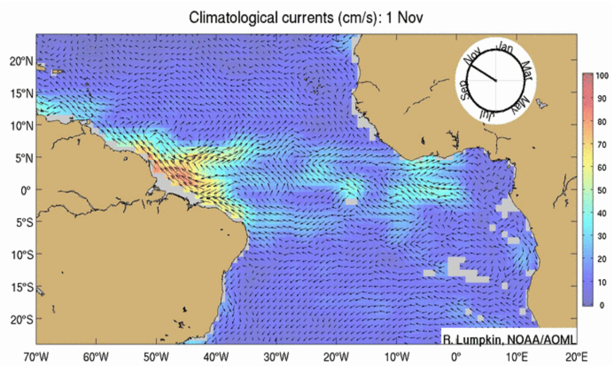

Figure 15. Many years of drifter deployments allow the creation of an ocean surface-current climatology. This may in turn be used to develop an optimal deployment strategy for the next decade (courtesy of Rick Lumpkin, NOAA-AOML).

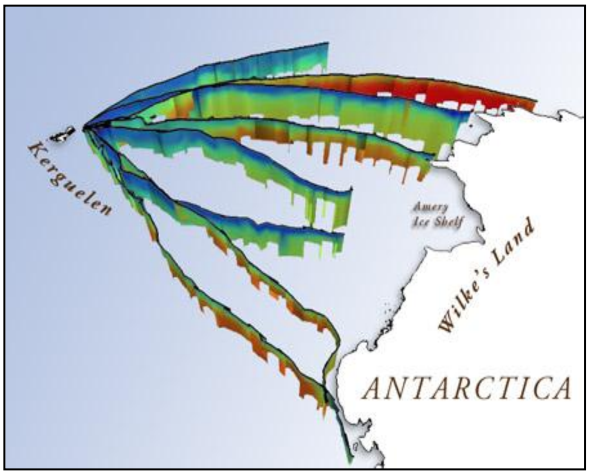

Figure 16. Ocean temperatures derived from profiles collected over 3500 dives by eight southern elephant seals migrating from Kerguelen towards Antarctica in Feb-Mar 2004 (courtesy of Sea Mammal Research Unit).

This in turn will allow a statistical estimation of the probable track of any drifter as a function of time. Such statistics will come into use over the next decade as a means of optimising the re-seeding of the drifter array in terms of assuring the continuous delivery of data from high-impact regions.

2.1.5 Quantifying and improving value for money.

Many impact studies conducted by national meteorological services over recent years have demonstrated that buoy data make significant positive impacts on forecast quality, particularly in areas where rapid cyclogenesis occurs (e.g. tropical oceans, north Atlantic). In other areas the impact is less well defined. So far little has been achieved in quantifying the value for money of buoy observations, although the capital and running cost of buoys is recognised as being comparatively low (see Sect. 1.4). Typically each observation made during the lifetime of a buoy will cost less than $1.0, less than $0.5 if Iridium is used as the satellite channel. The weather forecasting community also benefits from the DBCP barometer upgrade scheme, whereby non-barometer-equipped drifters being deployed by agencies other than meteorological services may have pressure observations added for a one-off payment of $1k.

In future, further improvements in value for money are likely to accrue from increases in buoy lifetimes (e.g. by using adaptive sampling algorithms, more energy-efficient transmission schemes and/or solar panels), from a more structured re-seeding strategy (see Sect. 2.1.4)

2.2 Deployment issues

As noted above, improvements in deployment strategies will in due course yield cost benefits. Nonetheless, most drifter deployments are made from ships-of-opportunity, and there will always remain areas where re-seeding is difficult to achieve. A major function of the DBCP and Argo Technical Coordinators will continue to be the search for deployment opportunities using any available shipping, including the use of charter vessels and deep-sea yachtsmen.

The reintroduction of air-deployable packages will be re-examined, although the costs of air certification are significant.

2.3 New platforms - marine animals as data buoys

A major growth area over the next decade will be the use of tagged marine animals, notably seals, as carriers of oceanographic packages (Fig. 16). Some such animals, fitted with satellite tags, are already transmitting oceanographic profile data on to the GTS. The closer alignment of the DBCP with sea mammal research groups is also yielding benefits in terms of collective approaches to sensor development and the negotiation of satellite air-time agreements.

3. CONCLUSIONS

The next decade of data buoy observations will see the gradual rollout of new sensors, particularly those capable of making reliable measurements of biological observables, an increased reliance on modern two-way satellite communications systems and improved energy efficiency and buoy lifetimes. Data timeliness will continue to improve, as will the global distribution of drifting buoys through the development of statistically justified re-seeding strategies. Overall costs are likely to remain more or less stable, as efficiencies in manufacturing and communications charges are offset by the need for improved sensors and the costs of deployment in remote areas. The success of the DBCP and the JCOMMOPS technical coordinators mean that it is likely that this coordination mechanism will continue in place for the coming decade, and will serve as a model for the coordination and outreach for other components of the ocean observing system.

4. REFERENCES

1. Sybrandy, A., Niiler, P., Martin, C., Scuba, W., Charpentier, E. and Meldrum, D. (2009). *Global Drifter Programme: Barometer Drifter Design Reference*. DBCP Report No. 4 revs 2.2. www.jcommops.org/doc/DBCP/svpb_design_manual.pdf

2. Charpentier, E. and Viola, H. (2009). *DBCP Quality Control Guidelines for GTS Buoy Data*. www.jcommops.org/dbcp/doc/qc/DBCP_QC_guidelines.pdf

3. Bernard, E. & Co-Authors (2010). "Tsunami Resilient Communities" in these proceedings (Vol. 1), doi:10.5270/OceanObs09.pp.04.

4. Viola, H. (2009). DBCP buoys by country. www.jcommops.org/dbcp/network/dbcpmaps.html

5. Viola, H. (2009). Barometer buoys. www.jcommops.org/dbcp/platforms/barometer.html

6. Ocean Observations Panel for Climate (OOPC). (2009). Essential Climate Variables. ioc3.unesco.org/oopc/obs/ecv.php